

**ONR Grant N000014-96-1-0361 Final Technical Report:  
Seafloor Geomorphology, Gas and Fluid Flow, and Slope Failure on the  
Southern Cascadia Continental Margin**

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**Project Summary**

Multibeam bathymetry and reflectivity data collected for ONR's STRATAFORM project on the northern California shelf and slope imaged distinctive geomorphic features and regions of anomalous reflectivity. In order to determine the relationship between these features and fluid and gas we analyzed industry and high-resolution multi-channel seismic data, Huntex seismic data, and side scan imagery. We found that subsurface gas is widespread in the STRATAFORM area. Furthermore, most subsurface gas was distributed parallel to isobaths and oblique to structure, suggesting that stratigraphy plays a prominent role in controlling or inhibiting gas migration to the surface. Pockmark distribution (evidence for gas expulsion) showed the same distribution, although skewed to deeper water depths (> 400 m) than the zone of maximum subsurface gas. Gas in the water column, imaged as plumes in 3.5 kHz profiling data, occurred across the shelf, again insensitive to subsurface structure.

ROV dives to the area, however, demonstrated that all of the active seeps occurred above structural features, and that all of the seep and pockmark features that occurred between structures were dormant and in fact acting as sediment sinks. We observed that structural highs were regions of localized increased carbonate precipitation (related to bacterial oxidation of venting methane), which serves to armor the seafloor and increase the acoustic reflectivity.

**Long Term Goal**

The long term goal of this project is to understand how tectonics, gas, and fluid flow act as forcing agents in the creation and modification of submarine geomorphology.

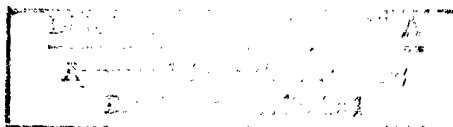
**Scientific or Technological Objectives**

The objective of this project is to evaluate the role of fluid flow, overpressuring, and gas migration in the creation and moderation of submarine geomorphology. This project addresses questions about: 1) the lateral and vertical extent of detectable overpressured fluids and gas in the subsurface, 2) gas-related structures and manifestations of flow on the surface, 3) seafloor geomorphology related to gas and fluid expulsion, and 4) structural controls on gas and fluid conduits and expulsion sites.

We pursued answers to these questions using a combination of theoretical and observational analyses. Observations and hypotheses based upon remote sensing data (seismic reflection surveys with frequencies ranging from ~15 Hz to ~3.5 kHz, side scan sonar surveys, high resolution bathymetry) were groundtruthed with direct seafloor observation and sampling using a remotely operated vehicle (ROV) in August, 1997 (sponsored by MBARI). Our continuing work on remote sensing data and ROV observations provides the basis for analyzing the relationship between gas-charged fluids and slope failure. Fulfillment of these objectives will allow us to obtain a better understanding of the dynamic processes occurring on the southern Cascadia continental shelf and slope, and ultimately help address how sediment is transported from the shelf to upper slope, and from the upper slope to abyssal depths.

**Background**

Our previous ONR-sponsored work focused on seepage-induced spring sapping, where excess pore pressure gradients trigger slope failure. The Eel River basin is a prime study area because it has all the ingredients necessary for fluid overpressuring: tectonic compression, sediment loading, and hydrocarbon formation. Coastal tectonic uplift and high erosion rates



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June 30, 1998

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SUBJECT: FINAL PERFORMANCE REPORT  
ONR AWARD NO. N00014-96-1-0361

Dear Mr. Director:

Per ONR Research Grant No. N00014-96-1-0361 Grant Schedule Item, Reports and Report Distribution and Attachment 1 (Reports and Report Distribution), I am providing your two copies of our Final Performance (Technical) Report for the period ending 31 March 1998. The research project entitled, *Seafloor Geomorphology, Slope Failure and Fluid Expulsion on the Southern Cascadia Continental Shelf and Slope* is under the direction of Dr. Daniel Orange, Principal Investigator and Dr. David Clague Principal Investigator with MBARI.

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If you have any questions or need additional information, you may contact me by telephone (408)775-1788, or EMAIL [ziegler@mbari.org](mailto:ziegler@mbari.org).

Sincerely,

Suzanne M. Ziegler  
Grants & Accounting Specialist

Enclosures

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create conditions conducive to rapid and voluminous deposition of organic-rich sediments in the offshore Eel River basin. Previous work in the region showed evidence of both active gas+fluid expulsion and the presence of submarine landslides.

Sediments entering the Cascadia accretionary complex may initially contain over 50% water; during accretion this may be reduced to less than 10% by compaction, cementation and deformation. Thus, substantial amounts of pore fluid are either trapped in overpressured zones, or liberated to the seafloor, migrating to the surface along permeable fault zones, stratigraphic layers, mud diapirs and/or mud volcanoes. The initial pore fluid (seawater) may be augmented by exotic constituents, such as hydrogen sulphide, natural gas, or oil derived both from deeper sediments and devolatilization reactions. Thermogenic and biogenic gas in the Eel River basin may travel as dissolved constituents in fluids until the saturation point is reached and the gas comes out of solution. Such free gas can contribute greatly to the overpressuring and expulsion of fluids, and may play a significant role in shaping seafloor morphology. Gas and/or overpressured fluids may trigger submarine landslides because they provide a buoyancy force that offsets the gravitational forces acting on a column of sediment. Overpressured fluids can have dramatic effects on faulting at depth, the creation of mud diapirs and mud volcanoes, and slope failure at the surface. Because they originate in overpressured zones at depth and rise toward the surface, mud diapirs/volcanoes can provide an efficient conduit for fluid expulsion from depth. In the Eel River basin, our data document the presence of mud diapirs (Figure 1), indicating potential locations of gas and fluid expulsion.

Natural gas expulsion can also lead to cementation and armoring of the seafloor. Where fluids rich in gas exit the seafloor they can support chemosynthetic communities that include bacterial communities that metabolize natural gas as an energy source. In the process of metabolizing gas (methane) the bacteria produce bicarbonate, which by bonding with calcium available in seawater produces authigenic carbonate. The morphology of the carbonate provides clues to the vigorosity of expulsion, with chimneys and donuts representing strong expulsion and pavements and slabs indicating diffuse flow. Authigenically cemented surface sediments armor the seafloor and protect it from erosion. These cemented portions of the seafloor have anomalously high acoustic reflectivity, allowing their distribution to be inferred from remotely collected data.

## **Approach**

The Eel River basin experiences remarkably high sediment accumulation and tectonic uplift rates, and is known to be gas-prone in the subsurface. Based on our hypothesis that gas and overpressured fluids have an effect on slope stability in Southern Cascadia, we cataloged subsurface gas and fluid distribution and correlated it with geomorphic features on the seafloor. We first used industry-quality multichannel seismic reflection data (Figure 1) to determine the regional structural trends within the Eel River basin and document the general distribution of gas, gas-related features (e.g. mud volcanoes, breached anticlines, or diapirs), and overpressured fluids (Figure 2; Yun et al., in press). We then compared the distribution of gas and overpressured fluids with failure features noted on high-resolution bathymetric and acoustic reflectivity data. Use of high-resolution sidescan sonar and high resolution seismic reflection data facilitate documentation of localized areas of fluid seepage and finer-scale surface failure features. We also utilized industry "sniffer" data to look for evidence of gas in the water column to constrain areas that are presently venting gas and fluids. Observations and interpretations based upon these data were used to locate ROV dive targets and transects, and provide us with a framework for geologic modeling.

## **Accomplishments and Results**

### ***Pockmarks***

The distribution of pockmarks in the Eel River basin offshore northern California provides insight into gas+fluid migration and sediment accumulation processes acting on the shelf and slope of the continental margin. Pockmarks, conical depressions on the seafloor, serve as proxies for locations of discrete gas+fluid venting from depth. Numerous pockmarks

that litter the seafloor of the Eel River basin indicate that active gas+fluid expulsion is occurring or has recently occurred in this gas-rich sedimentary basin. The distribution and number of pockmarks on the seafloor appears to be inversely related to the location and amount of natural gas observed in the subsurface and inversely related to the locations of gas plumes in the water column (Yun et al., in press). The large number of pockmarks observed (up to 80 pockmarks per 500 meters along track) and size of each pock (> 10 m diameter) indicate that gas+fluid expulsion through pockmarks may be a significant force in redistributing sediment. The absence of pockmarks on the shelf contrasts with a large number of pockmarks observed on the slope, indicating spatially different sediment accumulation types and rates and varied modes of gas+fluid transport in this basin.

Correlation of surface failure features such as pockmarks with subsurface natural gas suggests hydrocarbon migration may be a significant geomorphic forcing mechanism acting on the seafloor of the continental margin. Analysis of seismic data in the Eel River basin shows that although natural gas in this area is abundant, it is regionally variable and controlled more by stratigraphy than by structure. The abundant gas detected in this basin may affect sediment strength and slope stability, altering both seafloor morphology and sediment transport.

#### ***Preliminary ROV Observations***

Observations made during an MBARI-sponsored 11-day ROV program in August, 1997 indicate that gas and fluids are being actively expelled only along structural features in the Eel Basin, suggesting that the pockmarks on the slope between structures were created some time in the past under different conditions. In contrast, on the shelf high rates of sediment accumulation and/or the increase in permeability due to sand deposition are effectively obliterating surface evidence of fluid expulsion events.

Abundant pockmarks catalogued using side scan sonar data and high resolution bathymetry show an increase of expulsion-related features on the upper slope of the continental margin, with the highest concentration of pockmarks within the Humboldt Slide. Such features were observed on high-resolution seismic reflection data as well. ROV dives into these pockmarks, however, indicate that these shallow (< 1 m) and broad features (10-50 m diameter) are presently inactive and act as sediment sinks. No pockmarks smaller than ~10 m diameter were encountered. We estimate that within the STRATAFORM area, over  $6.6 \times 10^5$  m<sup>3</sup> of sediment has been redistributed by fluid expulsion out of pockmarks. This same volume of space is presently acting as a sink. Using a rough estimated sediment accumulation rate of 2 cm/yr, the pockmarks formed less than 150 years ago and have since been a sedimentary sink.

On the shelf, ROV observations indicated that gas and fluid venting do not change the local seafloor morphology. Analyses of 3.5 kHz data suggested widespread active venting on the shelf, and analysis of industry seismic reflection data showed abundant subsurface gas that parallels isobaths. ROV observations, however, suggest most vents are fault and/or structurally controlled. Side scan data and ROV observations indicate a lack of pockmarks on the shelf. We suggest that the sandy sediments of the shelf have a high enough permeability to permit gas rich fluids to continuously vent to the seafloor, and/or vigorous storm-driven erosion prevents the preservation of expulsion-induced geomorphic features. Observed vent sites all occurred above subsurface structures (fault zones, breached anticlines), and consisted of broad areas of seafloor covered by bacterial mats, as well as small (< 2 cm diameter) holes on the seafloor actively venting intermittent streams of gas bubbles.

Based on the lack of observed venting between structures, we suggest that the observed pockmarks and slope failures were created during episodic, catastrophic events. This hypothesis is supported by data observed the high resolution multichannel seismic reflection data (collected in 1996 by Fulthorpe and Mountain) and observations made using an industry-quality data set. These data collectively show that the Humboldt Slide has failed repeatedly in the past, and that gas and fluids are presently trapped in the body of the slide along slide planes.

#### ***Extension of Slope Morphology Studies to Other Margins***

Our previous study into headless canyon formation (ONR N00014-93-1-0202) lead us to the question of slope stability on seismically active margins (e.g.: the Humboldt Slide). How

is it that the steepest local slopes occur in a region that produces some of the largest earthquakes in the world? Is it possible that a 18° slope is somehow more stable in Cascadia than a 1° slope in the Gulf of Mexico, almost 1,000 km from the nearest seismic center? Using NOAA bathymetry with 100 m grid spacing and GLORIA side-scan sonar data, we have mapped almost 100 discrete landslides on the continental slopes of Oregon, California, Gulf of Mexico (GOM), and the US East Coast between New Jersey and Maryland. Each margin represents a different tectonic environment- the convergent Oregon with the possibility of a 'megathrust' earthquake every 600 or so years, the transform California margin with a narrow shelf, highly eroded slopes and frequent earthquakes, the salt tectonics province of the GOM, and the passive New Jersey-Maryland slope with canyons similar to California, but far from the Charleston and Nova Scotia seismic centers. The study shows that Oregon has the fewest and smallest slides and the GOM has the most and the largest by more than an order of magnitude. The California and New Jersey/Maryland slopes have very similar size and distribution of landslides, suggesting that similar processes may be at work

### **Impact on Science, and Transitions Accomplished or Expected, If Any:**

Our studies show abundant subsurface gas and evidence of gas+fluid expulsion in areas containing surface failure features in Southern Cascadia, which strongly suggests a causative link between gas and changes in seafloor geomorphology. We have also correlated regions of gas expulsion with carbonate cemented portions of the seafloor which result in armoring of the surface sediment and anomalously high acoustic reflectivity. Given that gas is a common occurrence on continental shelves worldwide, results from this project should be suitable for extrapolation to other area, especially in sedimentary basins that experience high sediment accumulation rates and/or are near tectonically active margins. We have also shown that the combination of tectonic uplift and subsidence rates can be combined with seafloor morphology to determine the long term sediment preservation potential in this basin (Orange, in press). We are beginning to examine slope morphology in general in a number of tectonic settings to determine the forcing functions acting in each of these settings.

### **Relationship to Other Projects, if known:**

The observations and data from this project provide limits and inputs to the slope evolution models of Pratson, Coakley, Steckler and Syvitski. In addition, the hypothesis of seepage-induced spring sapping provides constraints for the slope failure/sediment accumulation models of Parker, Garcia, and Syvitski. The hypothesis of geomorphology-fluid linkage provided a basis for studying the STRATAFORM research area, and provides robust data for analyzing the gully and pock mark distribution in southern Cascadia (Gardner, Field, Prior). The initial side scan and high resolution seismic data collected in 1995, and the industry MCS data mentioned above, show that gas is abundant in the subsurface, and many slope failure features identified on the surface provide evidence of fluid involvement; this compliments the work of Evans and Driscoll in examining the relationship between seismic reflectivity and gas.

## Statistical Information:

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## Publications:

Suess, E., Bohrmann, G., von Huene, R., Linke, P., Wallmann, K., Lammers, S., Sahlig, H., Winckler, G., Lutz, R.A., and **Orange, D.** (1998) Fluid venting in the Aleutian subduction zone, *Journal of Geophysical Research*, v. 103, p. 2597-2614.

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#### **In Press:**

**Orange, D.L.**, (accepted) Tectonics, Sedimentation, and Erosion in Northern California: Submarine Geomorphology and Sediment Preservation Potential as a Result of Three Competing Forces, *Marine Geology*.

Yun, J.W., **Orange, D.L.**, and Field, M.E., (accepted) Gas distribution in the Eel River Basin and its link to submarine geomorphology. *Marine Geology*.

Goff, J.A., **Orange, D.L.**, Mayer, L.A., and Hughes-Clarke, J.E., (accepted) Detailed investigation of continental shelf morphology from a high resolution swath sonar survey over the Eel River Basin, northern California. *Marine Geology*.

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#### **Graduate students:**

2 Graduate Students (at University of California, Santa Cruz):

Brian G. McAdoo

Janet Yun

Number of female graduate students: 1

Number of minority graduate students: 2

#### **Service on committees/panels:**

DESSC (Deep Submergence Science Committee - formerly ALVIN review committee); 1993-present.

ONR STRATAFORM committee; Slope Working Group; 11/93 - present

JOI/USSAC 5 year proposal review panel, 1996.

Board of Directors, The Lyceum (a non-profit organization providing extracurricular education activities to primary and secondary school children in the Monterey-Salinas-Watsonville area); 9/94 - present

National Board of Directors, Surfrider Foundation. Grass roots environmental advocacy group; as a Board member, participate in oversight as well as strategic planning. (1/97 - present)

#### **Professional Societies:**

American Geophysical Union

Geological Society of America

American Association of Petroleum Geologists

Society for Sedimentary Geology (SEPM)

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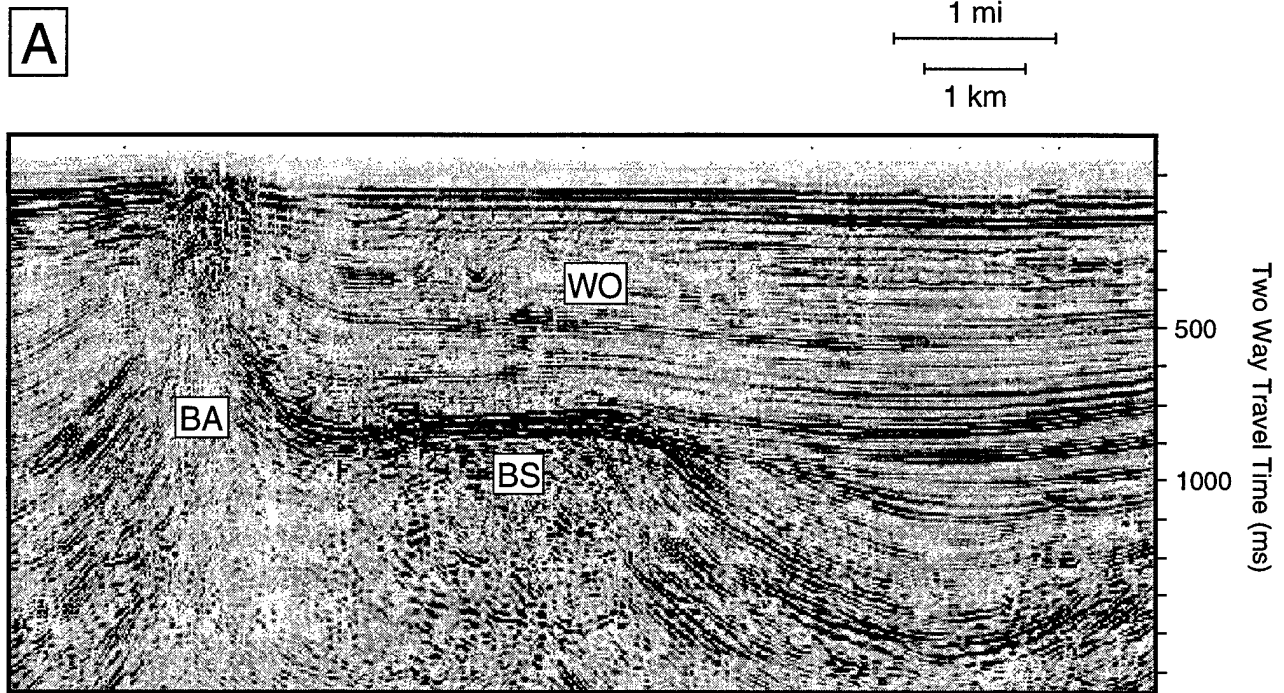


Figure 1: Example of industry multi-channel seismic line illustrating the style and distribution of subsurface gas. BS = Bright Spot; WO = Wipeout; BA = Breached Anticline

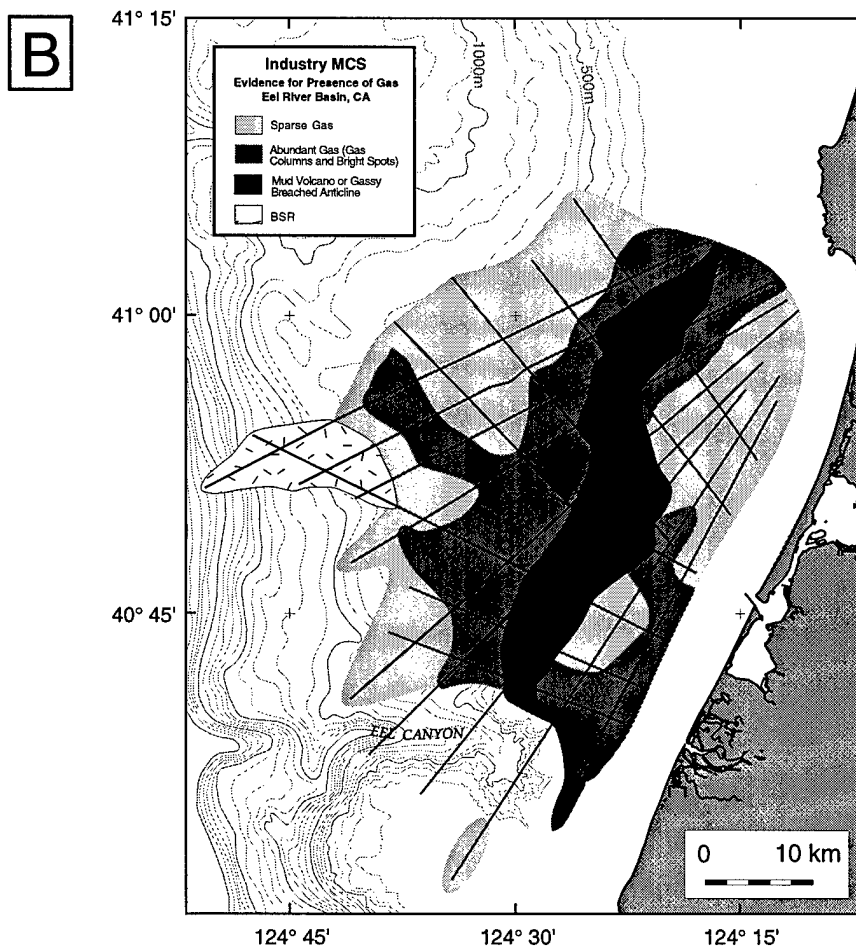


Figure 2: Distribution of subsurface gas based upon interpretation of Industry multi-channel seismic data (MCS). Similar interpretations were made using high resolution and Hunttec seismic data, side scan, and 3.5 kHz profiling (see Yun et al., in press)

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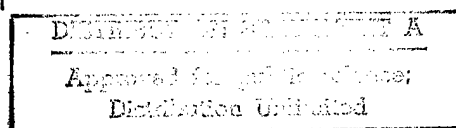
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